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13. ABSTRACT (Maximum 200 words)

In the research under the reported AFOSR grant, a number of new results were obtained by this principal investigator and his collaborators in the field of nonlinear optics and quantum electronics. The research progressed basically in these directions:

2.i Multiphoton optical resonances of a single cyclotron electron and electrons in semiconductors.
2.ii CW self-bending of a laser beam in sodium vapor/
2.iii Atomic shell x-ray radiation by electron beams in solid-state superlattice.
2.iv Dispersion-related multimode instabilities and oscillations in nonlinear counter-propagating waves.
2.v Bistable optical solitons
2.vi Nonlinear magneto-optics of vacuum
2.vii Other research

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Final Technical Report

Grant AFOSR 87-0152

Quantum and Nonlinear Optics Research on Solid-State X-Ray Source and X-Ray Laser Using Low Energy Electron Beams, Relativistic Nonlinear Optics, Self-Bending Effect, Bistable and Robust Solitons, Hysteretic Resonances in Semiconductors, Nonlinear Sagnac Effect and Isolas, and Related Fields

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Principal Investigator:

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1. Brief overview of technical results

This grant was activated on March 1, 1987 with the project period of three years ending on Febr. 28, 1990. The research of this principal investigator has been, in fact supported by AFOSR continuously for about ten years by now. During this period of time, under AFOSR support, the principal investigator authored or coauthored 120 publications, among them four book contributions, 43 regular journal papers, one patent, and 12 conference proceedings papers; the rest are conference papers.

In particular, during three years under the reported AFOSR support, more about 60 new papers have been published by this principal investigator and his group, among them 18 papers in regular journals [1-18], four book contributions [19-22], four conference proceedings papers [23-26], and 33 conference papers [27-88].

Most of the proposed principles are fundamentally novel and have initiated new opportunities in the field. The work by this principal investigator is highly credited by the international research community in the field. His work is frequently referred to by other workers. Within the last three years alone, for example, his work was referred to more than 240 times (according to "Science Index Citation") by other researchers (only those papers in which he was either the only or the first author, were counted). He was a member of program committees and panel member of several topical conferences and a workshop on nonlinear optics; in the same period, he was elected the Fellow of the Optical Society of America; in 1988 he was a Guest Co-Editor for a special issue of IEEE Journal of Quantum Electronics on "Quantum and Nonlinear Optics of Single Electrons, Ions, and Atoms."

In the research under the reported AFOSR grant, a number of new results were obtained by this principal investigator and his collaborators in the field of nonlinear optics and quantum electronics. The research progressed basically in these directions:

2.i. Multiphoton optical resonances of a single cyclotron electron and electrons in semiconductors.

2.ii CW self-bending of a laser beam in sodium vapor.

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2. Technical Reports on Specific Projects

2.i. Multiphoton Optical Resonances of a Single Cyclotron Electron and Electrons in Semiconductors

The interaction of microwave and optical radiation with a slightly relativistic single electron can result in strong nonlinear-optical effects [3,7,11 *]. These relativistic-based effects constitute the most fundamental mechanism of nonlinear interaction of light with matter. Recently this principal investigator predicted that even a slight relativistic change of mass of a single free electron may result in large nonlinear effects such as hysteresis and bistability in cyclotron resonance of the electron precessing in a dc magnetic field under the action of EM wave. Because of very low energy losses (which are due to synchrotron radiation), the relativistic change of mass to which the hysteretic resonance is attributed may be as strikingly small as $10^{-10} - 10^{-6}$. Subsequently, consistent with that prediction, the hysteretic (bistable) cyclotron resonance of a free electron has been observed by Gabrielse, Dehmelt, and Kells in an experiment in which a single electron has been trapped in a Penning trap for a period of time as long as 10 months.

In this research [3,6,7,11,12,16,21] this principal investigator continued to make progress in understanding of the intimate processes of nonlinear optics of single particles and in search of new effects which may have potentials of application in various fields of quantum electronics. The hysteretic cyclotron resonance occurs at the main frequency, i.e. in the situation when the driving frequency, Ω, is in the close vicinity of the unperturbed cyclotron frequency, Ω_0 (for the presently available dc magnetic fields the maximum cyclotron frequency is in the millimeter or submillimeter domains). It was most recently shown by this principal investigator [4,7,12] that the strongly nonlinear cyclotron resonance can also be excited by the *optical* pumping with a driving laser frequency (or frequencies) much higher than the cyclotron frequency. All the predicted optical excitations are, in fact, multiphoton processes.

2.i.1. Optical High-Order Subharmonic Excitation

First of these effect consists in generation of high-order subharmonics of a driving laser frequency. In this research it was shown [3,11] that homogeneous laser radiation in the visible or infrared domains with its frequency ω can excite high order subharmonics

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* In the Section 2, *only regular journal papers*, book contributions, and conference proceedings published under this grant, are cited.

(with the frequency Ω) close to the cyclotron frequency of free electrons Ω_c ($\Omega \simeq \Omega_c$) in the millimeter or microwave domains; excitation of subharmonic of the n-th order (the same as frequency division by the factor of n) means that $\omega = n\Omega$, $n \geq 2$ being integer. This *n-photon* effect may provide coherent links between lasers and rf or mw frequency standards. The laser power required for such a subharmonic excitation is strikingly low such that virtually any cw infrared laser can be used for this purpose. For example, in order to obtain 100-th order subharmonic of CO_2 laser ($\lambda \simeq 10$ μm), i.e., to divide its frequency by a factor 100 down to $\lambda = 1$ mm in one step, the cw power as low as $\simeq 10^{-6}$ W is sufficient.

The quest for optical one-step multiple transformation of frequency (by either multiplication or division) stems from the need to cover a gap between optical and microwave time & frequency standards. The conventional techniques are based on the frequency multipliers, complex frequency synthesis chains, frequency division based on locking both a laser and an rf source to a cavity, etc; some nonlinear optical methods based on generation of low-order subharmonics in parametric oscillators were proposed by this principal investigator earlier. The free-electron based high-order cyclotron subharmonics proposed in this research have potential to provide a promising alternative method for obtaining a direct coherent link between lasers and microwave frequency standards.

The nonlinear processes attributable to the excitation of cyclotron motion and sustained subharmonic oscillation when $\omega > \Omega_c$ or even $\omega >> \Omega_c$, are (i) the fast modulation of phase of an optical field seen by a rotating electron (which is essentially the Doppler effect), and (ii) the Lorentz force of EM field. Both of these mechanisms provide nonlinear links between cyclotron frequency Ω and driving frequency $\omega = n\Omega$. The characteristic feature of n-th order subharmonic oscillations of free electrons is that for each stable magnitude of the energy γ (and therefore for each orbit radius), the cyclotron motion can have n equally possible ***different equidistant*** states of the phase ϕ. This property is common for ***any subharmonic oscillations of the n-th order*** regardless of their origin.

2.i.2. Cyclo-Raman Scattering of Laser by a Single Electron

Another example of a multiphoton interaction of laser radiation with free electrons proposed and studied in this research [7,11,12,21] is a strong cyclotron resonance excited by biharmonic laser when two laser frequencies, ω_1 and ω_2, differ by either Ω (e.g. $\omega_1 - \omega_2 = \Omega$), or $n\Omega$ (i.e. $\omega - \omega_2 = n\Omega$) where n could be an arbitrary integer. These effects may be regarded as a three-photon and in general n-photon interactions respectively or, more specifically, as stimulated cyclo-Raman scattering of first and n-th orders. For some particular propagation configuration they can exhibit the so called isolas, i.e. completely isolated branches of the solution [7,11], which were shown to be

attributed to the existence of "prohibited" and "allowed" cyclotron orbits related to the forced "quantization" of the electron in the quasistanding laser wave. The most unified approach to all these effects using the general theory of nonlinear interaction of light with a single cyclotron electron was developed in [11]. This theory is based on the decomposition of electron motion into purely cyclotron component and noncyclotron components, the latter ones including all the higher-order oscillations with all possible frequency combinations. This approach allows one to obtain general results which are valid for arbitrary energy of electron excitation, and for arbitrary order of interaction.

In the multiphoton interaction of an optical laser with an electron, cyclo-Raman resonances offer a new method of excitation of the cyclotron motion which may prove more advantageous compared to conventional methods utilizing either mw or rf oscillators. Indeed, since the optical frequencies, ω_1 and ω_2, can be provided by two modes of the same laser, they allow for easily tunable control over the difference frequency $(\omega_1 - \omega_2)$. The power of laser light required to obtain the cyclotron excitation is sufficiently low to allow for the use of lasers in a cw or quasi-cw regime. The proposed effects may also be used for particle acceleration; even in a simple Penning trap, the kinetic energy of an excited electron as high as a few Mev, may be obtained. For the $n^{\underline{th}}$ order cyclo-Raman resonance, the excited electron can have n possible phases of cyclotron excitation (which differ by π/n); which phase is excited, depends on the initial conditions. This may be regarded as a manifestation of a new type of optical bistability which may be called phase multistability [3,7,12] (i.e. that based on multistability of the phase of oscillation rather than on multistability of its amplitude).

2.i.3. Dynamics and Stability of Hysteretic and Multiphoton Optical Resonances

Most of the nonlinear optical effects with a single cyclotron electron exhibit complicated nonlinear behavior, one of the main manifestations of which is multivalued solutions for steady-state regimes which result in such phenomenon as hysteresises, bistability, and, in general, multistability of the amplitude as well as phase. It is obvious that some of these steady states are stable whereas others are unstable. Therefore the stability analysis is an important component of the theory of the phenomenon. In this research, the analysis of the transient regimes in the system for all the nonlinear processes of interest has been performed [16]; it addresses both small-perturbation stability in the vicinity of the steady states and the behavior of the system in-large, i.e., when initial conditions are arbitrary (the so-called large perturbation). Very simple criterion of steady state stability for all the cases involved which is based on behavior of the electron energy versus driving intensity has been derived.

The stability of hysteretic cyclotron resonance, subharmonic optical excitation, and biharmonic optical cyclo-Raman resonances of a single electron was analyzed. A simple

criterion of small-perturbation stability was derived whereby for the main resonance and subharmonic resonances those states are stable for which the derivative of the electron energy with respect to driving intensity is positive and vice versa. For the cyclo-Raman resonances in the absence of isolated states (the so called "isolas") the stability criterion is the same, whereas in the presence of the isolas it is reversed above the point of self-crossing in each isola. The behavior of the system in-large using phase portraits was also explored and existence of "corridors of attraction" as well as phase multistability in subharmonics and higher-order cyclo-Raman scattering was demonstrated.

The existence of stable states of the excited electron especially in the case of high-order nonlinear excitation such as optical subharmonics and optical cyclo-Raman effect is significant for future experiments with laser excitation of cyclotron motion and for such physical applications of nonlinear cyclotron resonances as laser particle acceleration, phase optical bistability, and coherent links between laser and microwave frequency standards using high-order subharmonics (see preceding Section).

2.i.4. Hysteretic Three-Photon Cyclotron Resonance in Semiconductors

Most nonlinear effects discussed above are also feasible in some narrow-gap semiconductors which is attributed to pseudo-relativistic behavior of the effective mass of their conduction electrons. In the earlier research by this principal investigator it has been shown that the hysteretic resonance of a nature similar to that of a single electron in a free space at the main frequency may occur in narrow-gap semiconductors which is attributed to the pseudorelativistic properties of their conduction electrons.

In this research, a hysteretic three-photon resonance in narrow-gap semiconductors similar to that of a single electron in vacuum was predicted [6,23] which is based on the nonparabolicity of semiconductor conduction band giving rise to a pseudorelativistic effects. The generation of a difference frequency $\Omega = \omega_1 - \omega_2$ using the nonparabolicity of semiconductor by laser beams with frequencies ω_1 and ω_2 has already been demonstrated in the earlier work using either spin resonance, or cyclotron resonance. However, the hysteretic resonance has not been observed (or looked for) in [41,44] which might be attributed to the laser intensity apparently insufficient for such an effect. In this research it was shown that this effect is theoretically feasible in semiconductors such as InSb, GaAs, and HgTe, which are driven by two modes of CO_2 laser at 10.6μm and 9.4μm such that difference frequency corresponds to $\lambda \sim 83\mu$m, with the driving intensity being $10^5 - 10^6$W/cm^2. This effect may be of significant interest both for the study of highly excited Landau levels and for such applications as resonatorless optical bistability and far-infrared sources of coherent radiation.

2.ii. CW Self-Bending of a Laser Beam in Sodium Vapor

In this research [9,13,17], the first observation of CW self-deflection of an asymmetrical laser beam with a deflection angle up to eight diffraction widths, as well as strong attenuation of the on-axis radiation was achieved in a short sodium vapor cell. This effect was also used as a simple and straightforward experimental tool to determine the nonlinear refractive index of the sodium vapor, Δn; it was found that it varied almost linearly with intensity I, $\Delta n \simeq n_2 I$, with $n_2 \sim -10^{-7}\,\mathrm{cm}^2/\mathrm{W}$ at $\sim 200\,^\circ\mathrm{C}$ and intensities below $220\,\mathrm{W/cm}^2$.

Self-bending (or self-deflection) of a laser beam, first proposed by this principal investigator in 1969 and experimentally observed later in the same year, occurs when a light beam with an asymmetrical spatial intensity profile propagates through a nonlinear refractive index material, causing a nonlinear prism to be induced in the beam path. Various applications utilizing this effect are possible, including optical switching and interconnecting, resonatorless optical bistability, radiation protection and power limiting [9]. The effect can also be used to measure the intensity dependent refractive index $\Delta n(I)$, which, upon comparison with theory, can yield spectroscopic information, e. g., at near-resonance frequencies. Since the first observation of self-bending in a NaCl crystal, experiments have been limited to the use of pulsed lasers, resulting in time-integrated observations, as well as other complications which prohibited a complete study of the effect. Recently some indication of steady-state self-bending has been reported in liquid crystals, and long pulses were used to achieve self-bending in CS_2 using a powerful CO_2 laser in the infrared domain (at 10.6μm). On the other hand, the large nonlinearity in the vicinity of the D-resonances of sodium vapor enabled the first investigation of a *cw* self-action effect (self-focusing), as well as the effects of resonatorless optical bistability based on self-focusing.

In this research the first detailed study of visible *cw self-bending* in sodium vapor was performed. Typically, the experiment was done on the self-defocusing side of the resonance in sodium vapor to avoid complications related to self-focusing. When the laser was tuned just below the D_2 resonance (589.0 nm), and the vapor temperature was $202\,^\circ$C, the refractive index was predominantly Kerr-like, i. e., $\Delta n = n_2 I$, with $n_2 \sim -10^{-7}\,\mathrm{cm}^2/\mathrm{W}$.

An argon-pumped ring dye laser was used to achieve a frequency stabilized, single-mode beam. The beam was focused on the razor blade in front of the input face of the cell and then imaged into the cell (Fig. 5). The beam waist had a $(1/e^2)$ size of $220\mu\mathrm{m} \pm 15\%$ (without the razor blade). The laser was detuned until the maximum self-bending was observed: -1.9 GHz from the point in the D_2 line which produced the brightest resonance radiation.

At 214 °C ($N=7.0\times10^{12}\,cm^{-3}$) a self-deflection angle of 5.9 mrad, which is *eight* time the diffraction angle, θ_D, was measured [13,17] when the input beam power was 170 mW. This is a substantial accomplishment for a cw experiment; even in an earlier pulsed experiments with a laser power up to 400 MW/cm^2, the deflection did not exceed the diffraction angle. Self-bending was also observed on the *self-focusing* side of the resonance (where $n_2>0$), but measurements were difficult because the beam damaged the output window.

Our results [9,13,17] suggest a strong potential for applications such as radiation protection, optical switching and limiting, optical bistability, and nonlinear coupling. Presently, we started new series of experiments on self-bending using nonlinear optical properties of semiconductor superlattices based on ZnSe and GaAs. The goal of these experiments is twofold: to use this effect as very efficient and straightforward method of measuring the spectrum of the nonlinear refractive indices in these structures, and explore applications of the self-bending for fast optical limiters and switches. In our most recent research [26], the self-deflection effect has been used as a very simple and efficient tool for nonlinear spectroscopy of exciton resonant line in a semiconductor; for the first time to the best of our knowledge, direct measurement of nonlinear refractive index spectrum in ZnSe using self-bending of a pulsed laser beam, has been done.

2.iii. *Atomic Shell X-ray Radiation by Electron Beams in Solid-State Superlattice*

Soft x-ray can be generated by low energy electron beams traversing a periodic layered medium with very short spatial period as was shown previously in the earlier research by this principal investigator in collaboration with Datta. In this research [8,24] done by this PI in collaboration with his post-doc C. T. Law, it was demonstrated that a combination of materials with high and low atomic numbers can produce an intense x-ray radiation with very narrow spectral peaks at the vicinity of K, L, ... atomic absorption edges of each of the materials due to a strong anomalous dispersion at the edges. X-ray absorption, electron scattering losses, Bremsstrahlung radiation, and their influence on the maximal power of the radiation, the required electron energy, and the optimal total thickness of the superlattice were also investigated. It was shown that the losses due to the photoabsorption and electron scattering can easily be compensated by a moderate increase of electron beam energy. The selection rules for materials constituting the solid-state superlattice was proposed. The results of this research demonstrate that an inexpensive x-ray source with mega- and submega-electron volt energy of electron beam can be used to generate narrow-line x-ray radiation.

When an electron beam traverses the interface between two semi-infinite dielectric materials with different dielectric constants ϵ_1 and ϵ_2, it emits the so called transition

radiation. This radiation can be enhanced by using a periodic multilayer medium instead of a single interface. Usually the spatial period of the layered structure is much larger than the wavelength of radiation. In this case ultra-relativistic electrons with energies 100Mev-50 Gev are required to excite the transition radiation. However, with the advent of new technologies, periodic layered structures (and even superlattices) can be constructed with a spatial period less than 100 Å. These structure are widely used as x-ray mirror. In the earlier research by this PI it was proposed to use these structures in order to obtain resonant transition radiation exploiting electron beams with very low energies. In solid-state structure, however, electron scattering and photoabsorption may be the main obstacles to achieving an effective source of x-ray radiation. In this research [8], it was shown that a slight increase of the electron beam energy renders insignificant the losses (due to scattering of electrons) and Bremsstrahlung radiation, while photoabsorption imposes an energy ceiling above which an increase in electron beam energy produces no significant improvement.

For the transition radiation, electromagnetic field is generated due to the difference in dielectric constants between the neighboring layers and the power of the radiation is proportional to $|\Delta\epsilon|^2 = |\epsilon_1(\omega)-\epsilon_2(\omega)|^2$ where $\epsilon_{1,2}$ are dielectric constants of the materials constituting the layered structure. Therefore, dispersion of dielectric constants of the materials strongly affect the optimal radiation and the shape of the radiation spectrum. In this research [24], it was investigated how the effect of anomalous dispersion in the dielectric constant which is due to photoionization transitions of electrons from atomic shells (as well as transitions between these shells) affects the radiation spectrum, and demonstrated that resonant peaks with narrow spectral width in the vicinity of the absorption edges can be generated. Based on these results as well as on the study of losses due to photoabsorption and electron scattering, [8, 24] the rules for selection of materials constituting the solid-state superlattice were proposed. When ultra-relativistic electrons are used to obtain the transition radiation, light elements with small atomic number are used as radiators and air plays a role as a spacer. Since a solid-state structure has to be used in order to employ low-energy electron beams and the value of $\epsilon-1$ is roughly proportional to the number of electrons which increases with atomic number of an atom, heavy elements with large atomic number become appropriate candidates as radiators and light elements as spacers in order to obtain a larger quantity $|\epsilon_1-\epsilon_2|$ (at least in a short-wavelength domain). The use of materials with large atomic number is further justified by the fact that many absorption lines of these materials fall within the soft x-ray domain (0.1 - 2 kev).

2.iii.1. Photoabsorption, Electron Scattering, and Radiation Optimization

The contribution of photoabsorption and electron scattering to the transition radiation can be estimated using notion of averaged absorption coefficient and the so called critical length which is defined as the length at which virtually all electrons are scattered and absorbed. The theory developed by us in [8,24] incorporates these two processes into the theory of the transition radiation in layered structures and allows one to find the optimal geometrical configuration (i.e. number of layers and thickness of each layer) so that the radiation is maximized in the desired frequency domain.

We have discovered that even when the spatial period of the structure is optimized for each particular energy there is some *maximum* meaningful energy ("ceiling") of electron beam which is related to the photoabsorption. With the typical value of the reciprocal absorption coefficient $\simeq 1\mu$m at $\lambda \simeq 10$Å, one obtains $E_{max} \simeq$ 7 MeV. For light materials this ceiling may reduce to 2 MeV, and even lower.

The *minimum* electron beam energy required to obtain appreciable intensity of radiation is achieved when electron scattering results in the same losses as photon absorption. The typical value of the reciprocal absorption coefficient is of the order of a few microns around a wavelength of 10 Å. For example when this value is $\simeq 5\mu$m, the minimal electron energy is about 100 KeV. Above this energy, photoabsorption begins to dominate over electron scattering. The Bremsstrahlung radiation can also be shown to be insignificant above this energy.

2.iii.2. Atomic Shell Resonances of Transition Radiation

The intensity of transition radiation is directly proportional to $|\epsilon_1 - \epsilon_2|^2$ where $\epsilon_{1,2}$ are respective dielectric constants of the both materials of periodic structure; it also strongly depends on photoabsorption coefficient. Both of these parameters undergo large change near the so called atomic absorption edges at which the absorption rises sharply. Because of the sharp changes in the atomic scattering factors one must expect a significant resonant increase of radiation intensity in the vicinity of these atomic absorption edges of either of two materials. For each particular element, these atomic absorption edges (and related resonances of refractive index) correspond to the photo-ionization of bounded electrons from their respective atomic shells (K, L, M ...) to the ionization continuum.

The most known effect related to this electron transition, is almost discontinuous jump of absorption as the photon energy increases in the vicinity of resonance. The points at which absorption increases almost discontinuously due to photo-ionization of K, L, M or N electrons are called K, L, M, N absorption edges respectively. The most pronounced absorption edges correspond to inner atomic shells. Most of the elements

have at least one absorption edge in the soft x-ray domain.

The less known (or rather less used) phenomenon is a resonant anomalous dispersion of a real component of dielectric constant at absorption edges, which can result in quite a drastic change of refractive index. For example, although the common notion is that the refractive index n for x-rays is slightly less than unity, the resonant dispersion at absorption edges can result in n being significantly greater than unity. It can readily be noticed, however, that anomalous dispersion in the x-ray domain must have a major importance as far as the Cerenkov and transition radiations are concerned since the behavior of $n(\omega)-1$ (in the Cerenkov radiation) or $n_1^2(\omega)-n_2^2(\omega)$ (in the case of the transition radiation), determines the very existence of these phenomena.

In this research [24] the dielectric constant and absorption in the vicinity of the atomic shell resonances (i.e. absorption edges) was calculated using the theory of atomic scattering factors. For very high frequencies (i.e. for radiation in the γ-domain in which the photon energy is much higher than K-shell energy and therefore, all the electrons can be regarded as free), the number of electron/atom participating in the interaction, is the same as the total number of electrons in an atom, Z, and the formulas for dielectric constants become a simple plasma formula for the free electron gas. Elements with Z= 1 to 4 have their K absorption edges below 0.2 kev. However, there are many absorption edges of elements of high Z falling within the soft x-ray domain. In the general case of arbitrary frequency, each bound electron in an atom can be treated as an oscillator and the summation of the scattering factors from each atomic shell q gives the resulting atomic scattering factor. The resulting formulas for the atomic scattering factors are essentially the counterparts of the Kramers-Kronig relations for these factors. Unfortunately, the known experimental data do not provide any significant information on the atomic scattering factor attributed to the anomalous dispersion in the very close vicinity of absorption edges, i.e. in the domain being of the most interest for this research. Apparently this is related basically to the fact that so far, there were no immediate practical needs for this kind of data. The theoretical calculations of the resonances of real component of the dielectric constant in this research were based on the Kramers-Kronig relations for these atomic scattering factors.

All solid elements have sharp resonance at K-edge, beginning from Z=3, i.e. from lithium, whose K-absorption edge corresponds to $\lambda_K \simeq 226.5$Å; λ_K decreases as Z increases. Since the photo-ionization gives rise to sharp resonances only when electrons are excited from the inner-atomic shells, the L-shells can be used beginning from Z = 14 (Silicon, with the L-absorption edge at $\lambda_L \simeq 123$Å), M-shells beginning from Z= 48 (cadmium, with $\lambda_M \simeq 28,13$Å), and N-shells beginning from Z = 58 (cerium with $\lambda_N \simeq 100$Å; in this particular case, the N-shell resonance according to the known data becomes very sharp even before N-shell is completely filled up). For all these shells and elements, we have obtained in the explicit form the number of electrons participating in each particular interaction. This theory was used by us to calculate parameters of the

system for a few specific examples of materials. Although the increment p is not very well defined for L, M and N shells, the total error in the peak intensity of radiation with $p = 2$ does not exceed 10 - 20 %. The important factor that needs further detailed investigation, is the splitting of resonance for the higher shells (L, M, N) into sub-shell levels, which should reduce somehow the resonance peaks of atomic factors and therefore, the peak intensity of the transition radiation. However, the results obtained should be valid for K-shell lines. We also discovered that that the peak resonant magnitudes of atomic factors are insensitive to the variation of a damping parameter.

2.iii.3. Selection of Materials

Proposed method of x-ray generation is suitable to obtain radiation in the entire domain of wavelengths 1 - 200 Å. Using various combination of materials, a broad spectrums of x-ray radiation can be obtained. This method, however, can be envisioned as the most efficient way of generation of narrow x-ray lines radiation in the vicinity of absorption edges of various elements where dielectric constant ϵ varies drastically. The idea is that for each desired frequency the alternating layers are chosen in such a way that one of the materials ("radiator") of the multilayer structure has its resonant frequency (i.e. frequency of one of its absorption edges) in the vicinity of the desired frequency. The other material ("spacer") must be chosen in such a way that its absorption edges are far from the chosen frequency of radiation. Another requirement for the spacer is that its absorption in the vicinity of desired frequency be minimum. For the most of frequencies of radiation the spacer must be a light element with a low atomic number. Yet another "technological" requirement is for each material to form stable layers with smooth surfaces. These requirements single out three light elements: B, Be, and C as the best candidates. Carbon is conventionally used in multilayers mirrors for x-ray domain. The advantage of using carbon is also that its surface is smooth and have stable boundary separation.

The radiator candidates can be chosen from the elements in the periodic table with one of their absorption edges close to the desired frequency. For the photon energy within the soft x-ray domain (up to 2 kev), elements for the radiator can be chosen from K, L, or M branches. The further selection of one of these groups is based on the absorption factor as well as the dielectric constant factor $|\epsilon_1 - \epsilon_2|^2$. At high photon energy (≥ 0.3 kev or $\lambda \leq 44$ Å), the rule of thumb is to choose the heaviest elements as the radiator because their dielectric constants differ the most from the light spacer. Consider, for example, the photon energy $\simeq 0.88$ kev corresponding to $\lambda \simeq 14$ Å; one can then that the radiator candidates are Ni and Ce (leaving aside Ne as a gas); the best candidate is Ce.

The procedure described above enables one to select couples of elements each one consisting of a heavy element (radiator) + a light element (spacer) for generation of

narrow line radiation with relatively high photon energy or short wavelengths (down to a few angstroms). At low photon energies, though, a light element may occur to be a good candidate as a radiator. Consider an example when the desired photon energy of radiation is 100 ev which corresponds to $\lambda \simeq 110$ Å. One can find then that the radiator candidates are Be, Al and Rb (with different shells). Since at low photon energy the absorption factor is larger for elements with high atomic number, Be is the best candidate. In order to design a narrow line radiator for longer wavelengths ($\simeq$44Å and longer) one has to use couples of two elements out of B, Be, and C. A combination of either two of these elements will form a system which would radiate at two frequencies out of three: 43.68Å or 284.84 ev (C), 66.0Å or 188.0 ev (B), and 111.0Å or 111.0 ev (Be). The energy of electron beam required for these structures to generate, are low and can vary from 200-300 kev to 1 Mev.

The advantages of C is its surface smoothness and stable boundary separation. The K absorption edges of C is at 0.283 kev. We have calculated the radiation efficiency versus photon energy for the cases with Carbon (C) as a spacer and Barium (Ba), Cerium (Ce), and Europium (Eu) as radiators. In general, the choice of radiator depends on the frequency domain desired. The absorption edges of Ba, Ce, and Eu are at 0.78 kev (M edge), 0.883 kev (M edge), and 1.11 kev (M edge) respectively. In the soft x-ray domain one should expect the resulting spectral density to have two peaks. The peak at low frequency is due to the element with low atomic number (which act then as a radiator) while the peak at higher frequency is due to the element with higher atomic number.

In our further research, we are planning to continue this theoretical effort, with the emphasis on the search of new layered structures for the radiating system (such as e.g. liquid crystals, percolation structures, multilayered X-ray interferometric mirrors, etc.), and on the possible applications of this system as an inexpensive source of narrow-line X-ray radiation.

2.iv. Dispersion-Related Multimode Instabilities and Oscillations in Nonlinear Counterpropagating Waves

In this research [15] it was shown that two linearly polarized counterpropagating waves in a Kerr-nonlinear medium (in particular, in nonlinear silica fiber) with linear dispersion can exhibit multi-mode temporal instability. The boundary of the unstable regime was found, and it was demonstrated that the fully developed instability results in self-sustained oscillations and onset of chaos. The cross-interaction of two counterpropagating light beams in a third order nonlinear material is a perceptionally simple but fundamental process with a host of potential applications. In the earlier research by this PI supported by AFOSR it had been demonstrated that the steady states of this interaction exhibit of light-induced nonreciprocity attributed to the cross-

interaction of counterpropagating beams of light in a Kerr-nonlinear material which could result in a large enhancement of the Sagnac effect and directional switching of waves in a nonlinear ring resonator; nonlinear eigenpolarizations of the system had been found, and polarization transformation, switching, hysteretic states as well as "isolas" exhibited by the beams with arbitrary input polarizations has been predicted and studied.

Since the issue of instability (and especially temporal, or absolute instability) of intense counterpropagating waves in nonlinear materials is of great significance in such applications as lasers, optical gyros, and other optical devices, in this research done by this PI in collaboration with his post-doc Dr. C. T. Law, a theoretical study of temporal stability of nonlinear counterpropagating waves [15] has been undertaken. Nonlinear medium having finite relaxation time has previously been shown to exhibit temporal instability and chaos as the driving intensity exceed certain threshold for the simplest eigenpolarization (with two counterpropagating beams having linear polarizations parallel to each other). Subsequently periodic and chaotic temporal behavior was demonstrated in the same system for various nonlinear eigenpolarizations [83]. However, the relaxation of nonlinear refractive index may not be the most likely mechanism of instability since it imposes too stringent requirements on relaxation time.

In this research [15] it was demonstrated that another factor, namely regular linear dispersion (i.e. frequency dependence of refractive index) can be a natural and universal agent for temporal instability in the system. Although linear dispersion can give rise to well known nonlinear optical effects such as spatial instability of single plane wave and solitons in nonlinear fiber, this factor has never been discussed, to the best of our knowledge, in application to the problem in consideration.

Below the threshold of instability the system is stable although it can exhibit large amplification at the frequencies adjacent to the pumping frequency. In the region above the threshold there are numerous solutions for the boundary of instability, each one corresponding to an individual mode of oscillation which can be viewed as the longitudinal modes in a light-induced, distributed-feedback resonator. The (enveloping) threshold intensity increases as dispersion decreases. The necessary condition for initiating instability is that the signs of nonlinearity and dispersion must be opposite which coincides with the necessary condition for formation of a soliton and spatial instability in single-wave propagation.

Using as an example a 1 km long single-mode fiber with Ge-doped silica core at wavelength 1.55 μm with group velocity dispersion $D(k) = 6.5\times10^{-3}$ [note that $\mu = D(k)k^{-1}c^{-2}$], refractive index = 1.44, and $\chi = 3.2\times10^{-16}$ cm^2/W [86], in the lossless approximation, one finds the threshold intensity I_{cr} for such a fiber to be 6.7×10^8 W/cm^2, which is below the damage threshold 10^{10} W/cm^2 for fused silica [87]. Raw estimate shows that the losses existing in the real fiber ($\sim$0.5 dB/km [86]) would require about two times higher threshold intensity. If we use the SF-59 glass with

$\chi = 7\times10^{-15}\ cm^2/W$ [88] at wavelength 1.06 μm and assume $D(k)=12.7\times10^{-3}$, the same as for plain glass, the critical intensity is reduced to $\sim 2\times10^7 W/cm^2$ for the same length.

We are planning to extend this research into investigation of amplification for a probe field in such a system when the driving intensity is below the threshold of instability. Our preliminary results show that even if the driving is 15-20% of that threshold, the amplification for a probe wave can be much higher than for any other known four-wave mixing principle,

2.v. Bistable Optical Solitons

It was demonstrated by this PI earlier that the generalized nonlinear Schrödinger equation with certain nonlinearities allows for the existence of multi-stable single solitons (i.e., singular solitons with the same carried power but different profiles and propagation parameters). In this research [1,5,10,14] done by this PI in collaboration with R. H. Enns and S. S. Rangnekar (Simon Fraser Univ., BC, Canada) it was shown that while some of these new solitons are absolutely unstable, the rest fall into two classes of either "weakly" (i.e. stable against small perturbation) or absolutely stable solitons (the so called "robust" solitons that are stable against arbitrary perturbation, in particularly in the form of collision with another large soliton). The criteria for both weak stability and robustness were suggested and tested in computer simulations for various models of nonlinearity. In nonlinear optics, these solitons may exist either in the form of short bistable pulses, or bistable self-trapping (both two- and three-dimensional).

Bistable solitons present the ultimate case of multistable wave propagation and may provide new opportunities in the field of optical bistability. Indeed, for example, a bistable self-trapping of light provides a potential for optical bistable device entirely free either from any cavities, nonlinear interfaces, nonlinear waveguides, four-wave mixing, etc. Probably most importantly, bistable soliton pulses in nonlinear fiber waveguides with an appropriate nonlinearity may provide the first (to the best of our knowledge) known opportunity to attain a temporal (or dynamic) bistability as opposed to all known kinds of optical bistability which were so far formulated in terms of steady-state regimes. The very notion of steady-state optical bistability comes into the inevitable contradiction with the applications most of which assume fast pulse regime of operations. The truly dynamic (or temporal) bistability discussed here is based on bistable pulse shapes (as well as on bistable duration of the pulses) and offers a way to resolve this contradiction.

2.vi. Nonlinear Magneto-Optics of Vacuum

Our most recent research [18,25] demonstrated that the photon-photon scattering of intense laser radiation in vacuum predicted by QED can give rise to second harmonic generation (SHG) in a dc magnetic field; the laser energy required to observe this effect can be attained using existing systems. The photon-photon scattering in a vacuum is perhaps one of the most fun : :nental QED effects giving rise to nonlinear optical effects. However, none of the previously proposed effects has been observed in the experiment. Recently in collaboration with his graduate student Y. J. Ding, this principal investigator have demonstrated the feasibility of new nonlinear magneto-optical effects in a vacuum that gives rise to optical second harmonic generation (SHG) under the action of both strong dc magnetic field and high intensity optical laser radiation [18,25]. It has been shown that by using pulsed magnetic field $\sim 8 \times 10^6$ Gauss, and NOVA laser system with the laser energy of 6-10 KJ/pulse in each of 10-12 beam lines, one can obtain the averaged number of the second-harmonics photons per pulse significantly exceeding unity within a single laser shot, which is perfectly detectable with the-state-of-the-art photo-counting technology, Using averaging of photon counts over many pulses of laser, one can use also eximer or CO_2 lasers with relatively high repetition rates; when using these lasers, the number of pulses required to observe the effect is $\sim 10^6 - 10^7$. It has also been shown that SHG from the plasma of the ionized residual gas becomes negligible compared with vacuum contribution when the vacuum pressure is $\lesssim 10^{-5}$ torr.

2.vii. Other Research

The field on nonlinear interfaces, to which this principal investigator made pioneering contribution fourteen years ago, is still active. In this research this PI in collaboration with P. Smith and J. Tomlinson continued his activity to survey the field and outline new directions [20, 22]. This PI also took part in the research on the nonlinear optics of liquid crystals [4] and general nonlinear optical properties of materials [2]. Most recently, the long expected translation of his and his collaborators' book on nonlinear optics [20] has been published by Springer; the book was substantially updated to the original Russian publication and new material was added.

3. Work published under AFOSR support in 1987-1989

3.i. Regular Journal Papers

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[3] A. E. Kaplan, "Optical high-order subharmonic excitation of free cyclotron electrons," Optics Letters, 12: 489-491 (July 1987).

[4] F. Marquis, P. Meystre, E. M. Wright (OSC, Univ. Arizona), and A. E. Kaplan (Purdue Univ. Johns Hopkins Univ.), "Dynamics of the optical Freedericksz transition" Phys. Rev. 36A: 875-887 (July 15, 1987).

[5] R. H. Enns, S. S. Rangnekar (Simon Fraser Univ.), and A. E. Kaplan (Johns Hopkins Univ.), "Bistable soliton pulse propagation: stability aspects,"Phys. Rev. 36A: 1270-1278 (August 1, 1987).

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[12] Y. J. Ding and A. E. Kaplan, "High-order cyclo-Raman scattering of laser by a single electron," Phys. Rev. A, 38: 3109-3112 (Sept. 15, 1988).

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[15] C. T. Law and A. E. Kaplan, "Dispersion-related multimode instabilities and self-sustained oscillations in nonlinear counterpropagating waves," Opt. Letters, 14: 734-736 (July 15, 1989).

[16] Y. J. Ding and A. E. Kaplan, "Dynamics and stability of hysteretic and multiphoton optical resonances of a single slightly-relativistic electron," J. Opt. Soc. Am B., 6: 1299-1305 (July 1989).

[17] G. A. Swartzlander, H. Yin, and A. E. Kaplan, "CW self-deflection effect in sodium vapor", J. Opt. Soc. Am. B., 6: 1317-1325 (July 1989).

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3.ii. Books and Book Chapters

[19] V. S. Butylkin, A. E. Kaplan, Yu. G. Khronopulo, and E. I. Yakubovich, *"Resonant nonlinear interactions of light with matter,"* Monograph translated from Russian, with new chapters added, Springer-Verlag 1989, NY.

[20] A. E. Kaplan (Johns Hopkins Univ.), P. W. Smith, and W. J. Tomlinson, (Bell Commun. Res.) "Nonlinear waves and switching effects at nonlinear interfaces", invited chapter in the book *"Nonlinear Interfaces"* edited by G. Stegeman, to appear in 1990.

[21]*A. E. Kaplan and Y. J. Ding, "Nonlinear optics of a single slightly-relativistic electron," *"invitedchapter," to appear in the book *"Erice International School on Quantum Electronics: Nonlinear Optics; 1988."*

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3.iii. Conference Proceedings

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[25]*A. E. Kaplan and Y. J. Ding, "Nonlinear magneto-optics of vacuum," (*Invitedpaper) to appear in the Proceedings of the International Conference on Lasers'89, December 3-8, 1989, New Orleans, Louisiana.

[26] Y. J. Ding, C. L. Guo, G. A. Swartzlander Jr., J. B. Khurgin, and A. E. Kaplan, "Direct measurement of nonlinear refractive index spectrum in ZnSe using self-bending of a pulsed laser beam," to appear in the Proceedings of the International Conference on Lasers'89, December 3-8, 1989, New Orleans, Louisiana.

3.iv. Conference Papers

[27] Y. J. Ding and A. E. Kaplan "High-Order Multi-Photon Optical Excitation of Free Cyclotron Electrons," Intern. Conf. Quant. Electr., IQEC (Baltimore, May 1987).

[28]*A. E. Kaplan, "Bistable and robust solitons of highly-nonlinear Schrodinger equations" the Workshop "State of the Art Developments in Nonlinear Optics" (March 1987, Tucson, AZ). (*Invited paper)

[29]*A. E. Kaplan, "Bistable solitons and their application in Nonlinear Optics", the Sixth Intern. Conference on Mathematical Modeling (August 1987, St. Louis, MN). (*Invited paper)

[30]*A. E. Kaplan, "Nonlinear Optics of a Single Electron," Int. Quant. Elect. Conf (Baltimore, May 1987). (*Invited paper)

[31]*A. E. Kaplan, "Nonlinear optics of a single electron," XXII and General Assembly of the International Union of Radio Science (URSI) (Tel Aviv, Israel, August 24-Sept. 4, 1987). (*Invited paper)

[32] A. E. Kaplan, "Quantum Theory of Relativistic Hysteresis of a Single Driven Electron," the 1987 Annual Meeting of the Optical Society of America, (Rochester, NY, October 18-23, 1987).

[33] Y. J. Ding and A. E. Kaplan, "High-order Cyclo-Raman Excitation of a Single Electron by Laser," the 1987 Annual Meeting of the Optical Society of America, (Rochester, NY, October 18-23, 1987).

[34] A. E. Kaplan and C. T. Law, "Intense Resonant Lines in the Transition X-ray Radiation Due to Inner-Shells in Atoms," the 1987 Annual Meeting of the Optical Society of America, (Rochester, NY, October 18-23, 1987).

[35] C. T. Law and A. E. Kaplan, "Photo-absorption and Electron Scattering in X-ray Transition Radiation in Solid-State Superlattice," the 1987 Annual Meeting of the Optical Society of America, (Rochester, NY, October 18-23, 1987)

[36]*A. E. Kaplan, "Multistable solitons of a highly-nonlinear Schrödinger equation and their application in optics," the International Conference on Solitons and Chaos in Optical Systems (SOOS), San Jose State University, January 6-7, 1988.

(*Invited paper)

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[38] A. E. Kaplan and C. T. Law, "Intense Resonant Lines in the Transition X-Ray Radiation due to Inner Shells in Atoms," the 19th Annual Meeting of the American Physical Society, Division of Atomic, Molecular, and Optical Physics, Baltimore, MD, April 20-23, 1988; Bulletin of the APS 33: 1011 (1988).

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Applications, Houston, TX, February 2-4, 1989.

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[51] A. E. Kaplan and Y. J. Ding, "Nonlinear magneto-optics of vacuum", Conf. on Super-Intense Laser-Atom Physics, U. of Rochester, Rochester NY, June 28-30, 1989.

[52]*A. E. Kaplan, "Nonlinear optics of a single electron," Gordon Conference on Nonlinear Optics and Lasers, Wolfebore, NH, July 24-28, 1989 (*invited paper)

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DEPARTMENT OF THE AIR FORCE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
BOLLING AIR FORCE BASE, DC 20332-6448

REPLY TO ATTN OF: PKD (1Lt Cathy Gorton/202-404-7467) 25 Sep 91

SUBJECT: Effective Date Notice - Proposal Entitled "THIN FILM ROUTES TO NEW MATERIALS"

TO: Oregon State University
ATTN: Mr Clem LaCava
Administration Bldg. B306
P.O. Box 1086
Corvallis, OR 97339-1086

1. The effective date of the proposed subject grant as negotiated on 13 Sep 91 will be 01 Nov 91 subject to the availability of FY92 funds and any restrictions in the DoD Appropriations Act as passed by U.S. Congress. Costs incurred after the effective date, but in advance of the award date are allowable once the grant is actually awarded.

2. However, you are hereby notified that any costs incurred after the effective date will be at your own risk and not allowable on any Government grant in the event the subject grant is not ultimately awarded.

HARRY R. HARALDSEN
Contracting Officer

cc: NE/DR. WEINSTOCK
PI/Professor Sleight